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NASA PROJECT APOLLO WORKING PAPER NO. 1011

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PRELIMINARY STUDY OF A PULSE CODE MODULATION

TELEMETRY LINK FOR PROJECT APOLLO

[redacted]

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

SPACE TASK GROUP

Langley Field, Va.

February 24, 1961

APPROVAL

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TELEMETRY LINK FOR PROJECT APOLLO

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SPACE TASK GROUP

Langley Field, Virginia

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1.0 SUMMARY

This report presents the results of a preliminary study of the merits of a Pulse Code Modulation (PCM) or digital telemetry system which could be used in the Apollo spacecraft. Included are a brief description of PCM, a comparison of the present Mercury telemetry system with and without voice capabilities with an equivalent PCM/FM system, and a nonrigorous projected data handling capacity for Apollo using PCM/FM and also FM/FM. Some possible problems and design considerations, as well as ground station requirements, are discussed briefly.

The systems presented here are representative only and do not clearly indicate a preference for PCM/FM over FM/FM. In fact, the system capacities considered fall within the region where a choice between PCM/FM and FM/FM would probably have to be made, based on consideration of the payload capacity and mission goals. PCM/FM as shown here is definitely superior to FM/FM when power requirements alone are considered. On the other hand, FM/FM shows some weight reductions over the PCM/FM system. Hidden factors, such as the higher power supply weight resulting from the higher power requirements of the FM/FM system, can conceivably negate the apparent weight advantage of FM/FM over PCM/FM. No mention is made of the proposed system accuracy requirements which are also an important factor in choosing a modulation scheme, PCM/FM being superior for accuracies better than 1 to 2 percent.

2.0 INTRODUCTION

2.1 Pulse Code Modulation (PCM).- PCM is a method of converting a signal into a digital code. The most common method is to use a binary code. A PCM system is made up primarily of a commutator system and an analog to digital (A to D) converter with associated logic and programer circuitry. Data can be transmitted in a preset form or on a time-sharing or priority basis. The system flexibility is limited primarily by the programer flexibility. Amplitude signals must be sampled a minimum of two times per highest signal frequency cycle. These Pulse Amplitude Modulated (PAM) signals are digitized or converted into a coded signal consisting of constant amplitude pulses of one bit and zero bit. The resolution of the system depends on the number of bits (binary digits) used. In a comparison of PCM and FM subcarriers used to obtain PCM/FM and FM/FM, PCM/FM requires less bandwidth, driving power, and weight for large capacity systems with high accuracies for the same range and receiver conditions.

The discrete amount of error inherent to the system is tolerated in place of the uncertain error inherent to most PAM signals as noise. This discrete error is called quantizing noise and depends on the number of bits used. In operational use, quantization noise determines the signal-to-noise ratio of the system. If the decoder is set to trigger at one-half full amplitude, random noise less than half amplitude will not cause errors since only the presence or absence (or polarity) or a pulse is required for detection. PCM requires a greater bandwidth than PAM. An increased bandwidth improves the effective signal-to-noise (S/N) ratio as in FM. The S/N power ratio can be improved by increasing the difference in level between the one and zero bit. Above a certain range of level spacings, the S/N ratio improves quite rapidly over what it does below this range. This range of values of level spacing is called the threshold level and is dependent on the root-mean-square noise voltage in the system. Above this level, relatively little improvement can be obtained by power increases and the effective signal-to-noise ratic is determined primarily by quantization noise. This is not the case in other types of modulation. PCM makes more efficient use of bandwidth change as its discrete information content changes directly with linear bandwidth changes, whereas FM, PM and PAM respond logarithmically. Thus, relatively more discrete information content is possible in PCM when given a certain bandwidth.

Ground stations must be compatible with the system data format. The detected PCM signal is in a form adaptable to digital computers for rapid data processing. Analog read-outs can be obtained using a D to A converter.

3.0 BACKGROUND INFORMATION

3.1 Pulse Code Modulation (PCM).- (See fig. 1.) PCM is a means by which analog signals are converted into binary digital signals of yes-no serial pulses called "bits." A signal from a sensor, possibly a thermocouple or strain gage, is amplified, commutated and digitized. A specific number of bits is assigned to each sample. This number may be programed to vary according to what is being sampled. A digitized sample is commonly called a "word." Word separation bits and/or parity bits may also be included in a word. A parity bit is used to indicate or detect erroneous data. A preset number of words, usually corresponding to the number of samples of the master or fastest commutator, is commonly called a frame. At the start of each frame, data synchronization is usually inserted in the form of bits or whole words or the parity or word separation bit levels may be reversed. A cycle or major frame consists of the total number of frames required before each data channel is sampled at least once, and the slowest channel is sampled once. Data cycle synchronization is similar to, but usually more elaborate than frame synchroniztion. Possibly one or more words of one bit and zero bit or any bit combination prohibited from the data can be used for the cycle synchronization signal. Before data synchronization can be useful, bit rate synchronization must be given. For optimum efficiency, the data synchronization should also occur often enough to indicate bit rate, particularly in the NRZ (nonreturn to zero) system commonly in use. The entire signal including synchronization bits, is used to frequency shift key (equivalent to FM) a transmitter. Other modulation types such as AM or PM are available. Much of the information contained herein can be found in more detail in reference 1.

3.2 Input and commutation.- (See fig. 1.) Sensor signals are brought directly to the commutator. Low level signals are amplified in a strictly high level system. The commutator can be one unit or can consist of a master and one or more subcommutators of the same or different input signal levels. When subcommutators are used, a cycle can be described as the revolution of the slowest subcommutator and a frame as the revolution of the master commutator which selects the outputs of the subs plus its own input data. The master and subs are synchronized so that each time the master selects the output of a sub, the sub selects the next successive input data channel. The master and subcommutators can also provide synchronization excitation to the Analog to Digital Converter.

One method of doing this is to use one master channel and the slowest subchannel as synchronization generating points.

3.3 Analog to Digital (A to D) Conversion.- (See fig. 2.) The output PAM Analog signal from the commutator system is amplified as necessary and fed to the A to D Converter. Here the signal is sampled and compared to the output of an internal step function generator which is in serially decreasing or increasing fractions of the full-scale PAM signal in as many steps as there are data bits per word. This process is called quantization. If the signal is equal to or greater than the step signal internally generated, a yes-bit is stored in the register, which stores the bits until the sample is completely encoded, and the next portion of the signal compared. If the fraction of signal is less than the step fraction, a no-signal is stored in the register. After a sample has been fully digitized, it is shifted out to a logic circuit where synchronization, parity, separation, and other identification bits are added to the word in proper sequence and the whole word is then shifted out in parallel for recording and serially to the transmitter, possibly through a noise suppression filter. In this report, for simplicity only zero and full amplitude bits are considered. No mention is made of negative-positive combinations or NRZ codes.

3.4 Programing.- A programer is used to make the commutators, A to D converter, and logic circuitry an integral system. It consists mainly of time-base circuitry, timing pulse generators, a counter and a stable reference such as a crystal. By suitable programing, the number of commutator samples per second and also the number of bits per sample or word can be varied. Slowly varying signals may be sampled only a few times per cycle, and, if lower resolution is desired, the word-bit content can be decreased for this data, whereas a rapidly varying signal might be sampled quite often. If high resolution is desired, the word-bit content can be increased. The number of bits (n) per word in a binary system indicates 2^n discrete levels of information are available with a resolution of $\frac{1}{2}^n$. Continuous data and sampled analog data and digital data can be programed in with the commutated data on a priority or time-shared basis. In short, the flexibility of a given system is limited by the programer flexibility.

3.5 Modulation of transmitter.- The serial output from the logic circuitry is used to modulate the transmitter which sends out an RF signal. Several modulation methods are available.

Those most common to telemetry systems are FM, AM, and PM. AM is noisier than FM and PM which are mathematically equivalent. Lower input power is required for FM than AM for the same power out. FM is also most compatible with existing and planned ground station equipment. For these reasons, FM appears to be the most desirable even though its bandwidth is greater than for AM systems. In PCM/FM, we are Frequency Modulating or, more exactly, frequency shift keying, the transmitter carrier with the PCM serial pulse signal. This can also be done with PAM signals but an infinite number of deviations are obtained rather than discrete deviations as with PCM.

3.6 Synchronization.- Synchronization is used to reduce complexity of the ground receiving equipment and to compensate for drift in the transmitted bit rate and the analog to digital time base oscillator. Synchronization is also used to identify data. For good, accurate synchronization, the synchronization S/N (Signal to Noise) threshold at the receiver should be below the data S/N threshold. Synchronization can be simple as one bit per word or can consist of one or several words using bit combinations prohibited from the data such as full-scale value. For example, reference 2 indicates that for data synchronization the following rules apply:

(1) The number of digits must be less than an integral multiple of four

(2) Starting from either end of the word, the even groups of 2 digits must be alike, the odd pairs different

(3) The simplest patterns are for the number of digits to be equal to 3, 7, or 11 for synchronization

(4) Longer synchronization words are considered unlikely to be needed

Reference 3 indicates that the synchronization method used should reduce to a minimum transmitter and receiver complexity and minimize spectrum occupancy or bandwidth requirement. Compatibility with existing systems is also important. For a more detailed discussion, see section 5.0 of this report.

4.0 SPECIFIC SYSTEMS

In the following paragraphs, a few specific systems for different information contents are set forth. As a basis for comparison with equivalent FM/FM systems, a PCM/FM system with the same capacity as is required in the Mercury capsule telemetry system is first assumed. To assure adequate frequency response and to simplify comparison with standard IRIG FM/FM telemetry systems, a sampling rate of 5 samples per cycle of highest signal frequency will be assumed with the exception of the commutated data similar to that on the Mercury capsule. In many cases, this sampling rate is excessive as the minimum sampling rate according to the Nyquist sampling theorem is 2 samples per cycle to completely describe a constant frequency signal. The quantities and results used in the following are tabulated in tables I and II.

4.1 Equivalent Mercury System.- (See table I.) Using 90 commutated data channels with a commutator "revolution" of 1.25 revolutions per second, 112.5 samples per second are obtained. The PCM sampling rate to simulate IRIG FM/FM channels 5, 6, and 7 are, respectively, 20×5, 25×5, 35×5, or, 100, 125, and 175 samples per second, respectively. This gives a total of 513 samples per second. Assuming an 8-bit word with 2 word-separation bits (1 on either end of the word) and a parity bit, 11 bits per word are required. This will give a resolution of 1 part in 256 (2^8) or 0.39 percent which is more than can be expected of most sensors or FM/FM systems in general. If 1 master and 4 subcommutators are assumed where the master accepts each of the subs in turn, 1 frame synchronization per revolution of the master will be needed and 1 cycle synchronization will be required. The latter will occur after all subcommutator points have been sampled at least once. Based on the data inputs and frequencies, we will need about 1 cycle synchronization and 35 frame synchronizations per second. If the frame synchronization is derived by altering the word separation bits from yes to no or vice versa or doing the same thing with the parity bit, and using 3 words of full-scale or zero (yes or no) bits, we will need 516 words or 5,676 bits per second. Using the present IRIG PCM/FM standard of 1.5 cycles of bandwidth per bit, we would require approximately 8.5 kc of bandwidth or about $\frac{1}{5}$ that of the present Mercury system for the same information content. Assuming a required receiver bandwidth of 10 kc at 250 mc, a noise figure of 10 decibels (above 300° K) and an S/N ratio of 10 decibels a transmitter power of 20 milliwatts is required for 700 miles line-of-sight range using the Mercury Range sensitivity and gain figures. Based on current capabilities, an input power to the system of about 10 watts is needed with a weight of 5 to 6 pounds as opposed to Mercury's 50 to 60 watts and 7 to 8 pounds.

4.2 Equivalent Mercury System with voice added.- (See table I.) The same system capability as in paragraph 4.1 but with 2 voice channels added (to represent the HF and UHF voice transmitters in the Mercury capsule) will be considered. These 2 Mercury units require 6 kc of bandwidth each, draw 49 watts total, and weigh 8.5 pounds including the receivers and UHF backup transceiver. It should be pointed out that the increase in bandwidth will be greater for PCM/FM than for the 2 voice transmitters together, but this is to be expected since the voice units are amplitude modulated, not frequency modulated.

Using the same data content as before (513 samples per second) and using 5 samples per cycle of voice frequency which is more than necessary for intelligible speech but consistent with the rest of the system, a required frequency response of 790 cps, 3,950 samples per second per channel of voice or 7,900 samples total are required. Using the same cycle and frame synchronization as before plus a 2-word voice synchronization per voice channel, 8,420 words total or 92,620 bits per second are required. Therefore, the required bandwidth is about 140 kc. The system will weigh about 30 pounds compared to Mercury's 18 to 20 pounds, but we have a unified system and, considering that no RF multiplexer (7 pounds) and associated cabling are required, the weight of the 2 systems is about the same. Using the same considerations as before but with a receiver bandwidth of 140 kc, a transmitter output power of 0.5 watt for a total of about 30 watts input power is required, compared to the total of 109 watts for the equivalent Mercury system. This, of course, gives no consideration to the ground-to-air voice links which require a receiving system on the capsule. Power requirements would still be less than that for Mercury, however. The greater power needed by the Mercury system would require greater primary power which negates its weight advantage.

4.3 Possible Apollo System.- To determine what the characteristics should be for a PCM/FM system for the Apollo spacecraft, several assumptions must be made since specific requirements have not been put forward at this early date. These assumptions are:

(1) Commutated data as on Project Mercury - 135 channels

(2) Commutator equivalent speed - 1.25 revolutions per second

(3) 790 cps response voice channel - 2 channels

(4) 40 cps data channels - 6 channels

(5) Lunar surface probe and sampling data channels relayed by telemeter - 30 PAM samples per second each - 3 channels.

Using these assumptions and assuming 5 samples per cycle of "continuous" data (data not fed to very low frequency commutator), a total of 9,359 data words are required. (See table I.) Using a frame synchronization obtained by varying the level of the word separation bits or parity bits, a cycle synchronization of one 11-bit word, a voice synchronization of three 11-bit words per channel to indicate voice is now being transmitted and possibly to switch the signal to the audio equipment on the ground, and an indication of relayed data of five 11-bit words, 9,371 words or 103,081 total bits are required. This gives a PCM/FM RF bandwidth of 154,621.5 kc or approximately 160 kc. It should be pointed out that the synchronization patterns used are for example only and are not necessarily those recommended.

For an FM/FM system with the same capacity, the following subcarriers can be used, assuming standard IRIG bands:

Commutated data	- IRIG bands 13 and up
Voice	- IRIG bands 17 and up
40 cycle "continuous" data	- IRIG bands 8 to 14 and up
Relayed data	- IRIG bands 7 to 9 and up

If we are limited to the IRIG bands, which is a good assumption since most ground stations are compatible, the best way to accomplish the above is to use 2 transmitters, each with standard 125 kc deviation or 250 kc bandwidth as follows:

Transmitter 1 (High Frequency) - IRIG channels 7, 8, 9, 13, 17

Transmitter 2 (Low Frequency) - IRIG channels 8, 9, 10, 11, 12, 13, 18

Thus for an FM/FM system, 2 separate RF links at 250 kc bandwidth each would be required as compared to a PCM/FM system of 1 RF link with 160 kc bandwidth. Expected redundancy requirements would mean 2 identical systems on different frequencies (2 PCM/FM or 4 FM/FM transmitters).

4.4 Deep Space System.- (See table II.) For PCM/FM, it has been determined that a bandwidth of about 160 kc is required. For this study it will be assumed that the TRAC(E) system with its projected 1965 capability of 2,200 megacycles will be available. Using a carrier frequency of about 2,200 megacycles and assuming a vehicle antenna gain of 28 decibels, a ground station antenna gain of 51 decibels, cable losses of 16 decibels, a receiver input S/N ratio of 10 decibels and a recovery noise figure of 10 decibels for this bandwidth, the required transmitter power is 2.5 watts for a 210,000-nautical-mile range. For the capacity required, the system power and weight, excluding the transmitter, is estimated to be about 20 watts and 25 pounds respectively. The transmitter input power required and weight will be about 30 watts and 1 pound. The total system would then weigh approximately 26 pounds and require about 50 watts of input power at 28 vdc for ideal conditions (i.e., correct antenna orientation). For the same system capacity, we need 2 FM/FM systems with 250 kc bandwidth each. Using the same assumptions as before except as changed by the increased bandwidth requirements of about 275 kc on the ground and using 2 frequencies of 2,150 mc and 2,250 mc, a transmitter output power of 4.5 watts is required for the High Frequency unit and 4.5 watts for the Low Frequency unit. Including commutator, mixers, and VCO's, the total system weight would be about 18 pounds and require 110 watts of power input at 28 vdc.

4.5 Earth Orbital and Near-Earth System.- (See table II.) Since continuous contact with deep space antennas presently in existence is not possible within 8,000 miles above the earth, it is desirable to have the data transmitted on a lower frequency (UHF) compatible with existing world nets. Using the same data coding system for PCM/FM and the same commutator-subcarrier system for FM/FM, only different transmitters of lower frequencies will have to be used. Assuming a carrier frequency generated by taking a crystal oscillator output and multiplying its frequency up to 2,200 mc for the deep space system, the tenth subharmonic (220 mc) could be tapped off and used as the carrier for the UHF system. The same modulation could be used and be switchable along with the carrier frequency. Using frequencies in the vicinity of 220 mc and a receiver noise figure of 10 db and input signal to noise ratio of 10 db, a vehicle antenna gain of zero db, total cable loss of 4 db, and a ground antenna gain of 30 db, the following transmitter powers would be required:

PCM/FM - One transmitter with 2.0-watt output

FM/FM - Two transmitters with 3.5-watt output each

The system primary power and weight requirements are then:

PCM/FM - 40 watts and 26 pounds total

FM/FM - 90 watts and 15 pounds

4.6 Television capability.- Additional information such as real-time or slow-scan video may be required. Slow-scan video will, of course, increase the required bandwidth, but the increase would only be about 10 to 20 kc depending on the rate of scan. Real-time video, based on present standards of about 500 × 500 lines, would increase the bandwidth by 3 to 4 mc for PCM/FM. A system that has been proposed transmits a signal only when the degree of intensity on the scanning tube changes by a preset amount rather than transmitting each consecutive spot. This could possibly cut down the required bandwidth to 500 kc but will depend on the object scanned and the degree of resolution required. It is felt that video would not be transmitted continuously and possibilities exist for boosting the transmitter power either manually or automatically when video is to be transmitted.

4.7 Tracking and command.- By programing the A to D converter, sampling rates can be varied. It may be desirable to vary the sampling rate by ground command. The RF command link could also provide a voice carrier to complete the ground-to-vehicle voice link. Tracking can be accomplished using the carrier signal of 2,200 mc as in the TRAC(E) system for long-range and C-band beacon or Minitrack beacon for tracking at lower altitudes.

4.8 Discussion of results.- It is apparent that, at least in theory, PCM/FM is superior to FM/FM for long-range communications systems in accuracy and power requirements. It is evident from the examples given, however, that the greatest difference in power requirement is in the transmitter required. The weight difference between PCM/FM and FM/FM is less significant when the weight increase in the primary power supply, caused by the greater power required for the FM/FM systems, is considered. The system above does not reflect fully the basic advantages of PCM/FM over other systems such as FM/FM or PAM/FM. These advantages show up as weight reductions and power consumption reductions when the required accuracies are to be better than 1 percent and a large number of data channels (200 or greater) are required. For a large number of data channels with mixed accuracies, the PACM system, which is a system using time sharing of PAM and PCM, might suffice. This system has been developed by Aeroneutronics Division of Ford Motor Company. It should be mentioned, however, that the reliability and confidence levels are not as great for PCM as for other systems that have been in use for many years. This reflects the fact that PCM is a relatively new concept in data handling and has seen comparatively little usage to date in the field. It is anticipated, however, that in the next 2 to 3 years, much experience will have been gained in this field due to the already increasing interest in and usage of PCM. The foregoing development is not rigorous, but merely serves as a guideline presenting current thinking on the subject. Future study is recommended as the brief coverage contained here indicates. A somewhat more detailed discussion of possible problem areas follows.

5.0 SIGNAL BANDWIDTH AND NOISE CONSIDERATIONS

The preceding has been written assuming acceptable signal versus noise conditions for the transmitter and receiver. Some possible problem areas are described.

5.1 Random noise.- Random noise affects PCM occasionally whereas other systems are affected continuously. As a basis of detection, only the presence or absence of a bit, rather than actual amplitude or duration measurement, is used. Therefore, a relatively greater noise power can be tolerated in a PCM system than in a PAM or PDM system. If the noise amplitude, plus or minus, is less than $\frac{1}{2}$ of the pulse amplitude, no error occurs in decoding if the decoder is triggered at $\frac{1}{2}$ amplitude. Random or fluctuation noise can on occasion make the decoder see a pulse when there is none or not see one that is present. In a binary system there are only two levels. The difference between levels can be described by a constant C times the root-mean-square noise voltage at the decoder input v_n. Increasing C increases the level spacing. At a certain region of values of C, there occurs a rapid increase in the S/N power ratio where error probability due to noise diminishes considerably compared to values of C below these. The level described by the range of C is called the threshold and is determined by receiver noise characteristics and decoder characteristics and is a function of the system as a whole. This level can be arrived at mathematically using probability and statistical distribution theory and gives an ideal S/N power ratio of about 19 to 20 db with an error probability rate of 10^{-6}. S/N power ratios above this level do not improve the probability of accurate data reception to any great degree for an ideal system. In the examples used earlier, the use of 1.5 cycles of bandwidth per bit plus a receiver input S/N ratio of 10 db will give an effective S/N ratio to the receiver of about 19 to 20 db. In practical systems, the ground station characteristics may require another 20 db of S/N for proper detection and regeneration. By using a filter tuned to the pulse spectrum, we can eliminate some sources of noise in the receiver.

5.2 Quantization noise.- Since random noise can be effectively minimized by careful design, that is, increasing the S/N power ratio to the threshold level, the most prevalent noise in an operational system would be the effective noise introduced by quantizing the signal at descrete levels. Because of this fact, the accuracy of a PCM system is practically independent of the system length. Quantization noise gives rise to what can be called the effective S/N ratio of the system. Using an 8-bit information word, each digitized piece of information has a resolution of 1 part in 256 or 0.39 percent. This error is called quantization noise and will vary depending on the number of bits required per word. The primary difference between quantization and fluctuation noise is that quantization noise can be no greater than the difference between the two quantized levels closest together, whereas fluctuation noise can presumably take on all possible values. Thus we are introducing a rather discrete amount of error in preference to having unknown errors occur, as for example, in amplitude or duration systems. In a binary system, an increase in the number of bits reduces the quantization noise and increases the bandwidth. Thus, in PCM, the effective voltage S/N ratio increases exponentially as the bandwidth increases. This is not the case, say, for FM and PPM, for example, which respond linearly. In terms of decibels, the effective S/N ratio increases linearly for PCM and logarithmically for FM + PPM.

5.3 Bandwidth.- A coded system such as PCM utilizes more effectively an increase in bandwidth than would FM or PM systems. In the latter systems the receiver output effective S/N ratio responds linearly to bandwidth changes whereas a coded system responds exponentially. The channel information capacity of PCM is proportional to the bandwidth, whereas in most other broadband systems, channel information capacity is proportional to the log of the bandwidth. For the same information capacity, the S/N power ratio and bandwidth are exchanged logarithmically in PCM, whereas in most other broadband systems, the S/N power ratio is increased at the expense of bandwidth as shown in reference 4. Thus for a given bandwidth, a coded system has relatively more information capacity than normal broadband systems. Since, in a PCM system, the data is presented to the A to D converter in PAM form, we multiply the number of pulses per second into the A to D converter times the number of bits per sample, including synchronization and parity bits, to obtain the number of PCM bits or pulses required per second. If there are 11-bit coded words, then 11 pulses now represent one PAM pulse and the bandwidth is increased by 11 over the PAM signal bandwidth, and more discrete information per second is obtained. The bandwidth increase adds to the effective S/N ratio which is desirable. If the word-bit content is increased, bandwidth is increased, and the degree of resolution is improved exponentially. In an FM system, to double the resolution the bandwidth must be doubled, or, if the same resolution and double the data amplitude are desired for the same modulation index, the bandwidth is also doubled. In a PCM system, if the bandwidth is doubled, the resolution is squared. If double data amplitude is used, 1 bit more per sample for the same resolution is added. In these cases, signal power will have to be increased somewhat, however, for the S/N ratio to remain above the threshold. For the system described above, this would add less than 10 percent to the bandwidth for PCM/FM. In cases where reduced accuracy or deviation from normal-type information is acceptable, a lower word-bit content can be programed or commanded. This would result in decrease in required bandwidth greater than possible in FM systems.

5.4 The above discussion has, as its basis, a comparison between PCM and FM. This is equivalent to comparing the digitized or PCM signal to the FM subcarriers in telemetry systems. The consideration can be extended to PCM/FM and FM/FM. PCM/FM generally eliminates the need of subcarriers. This in itself reduces the required bandwidth. For double the amplitude with the same resolution of data signals in the preceding examples, the PCM/FM system bandwidth would probably be increased to 170 kc. The FM/FM system would be increased to 500 kc per transmitter. If PCM/FM bandwidth was increased to that of one FM/FM channel, a twofold increase in information content would be realized.

6.0 GROUND CAPABILITIES

Current ground station capabilities are not as extensive for PCM/FM as for FM/FM. Atlantic Missile Range is developing a PCM capability. The Mercury and Minitrack world nets do not have a PCM capability. For the most part, PCM is in a relatively early state of development. Receivers of the required sensitivity for a lunar mission are available. Instead of band filters and subcarrier discriminators, digital-to-analog converters or decoders will be required. By decreasing the bandwidth to the minimum required for the number of bits per second desired and by increasing the amplitude of the bits, a signal-to-noise ratio still acceptable at the receiver input can be obtained. This level is determined by the threshold level of the signal as well as the decoder triggering level, carrier deviation and bit rate. S/N can be maximized by providing a filter in the receiver system to limit noise outside the pulse frequency spectrum.

The output of the receiver system itself is in a form compatible with digital computers so that tape storage and data processing, as well as quick-look read-outs, can be accomplished at the same time.

With use of a correlation-type of detection, based on the expected drift of the transmitter time-base oscillator, the loss of data due to loss of synchronization is reduced by effectively reducing the synchronization threshold S/N ratio below that of the data threshold.

With narrow band systems when the receiver bandwidth is not too much greater than the signal bandwidth, some form of Doppler correction as phase lock must be used. The TRAC(E) system used in the earlier example does this so that close tolerances can be used.

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TABLE I.- DATA FORMAT

Parameters	Mercury telemetry		Mercury telemetry and voice		Apollo deep space telemetry		Apollo near-earth telemetry	
	FM/FM	PCM/FM	FM/FM	PCM/FM	FM/FM	PCM/FM	FM/FM	PCM/FM
Multiplexer channels	90	90	90	90	135	135	135	135
Multiplexer speed	1.25rps	1.25rps	1.25rps	1.25rps	1.25rps	1.25rps	1.25rps	1.25rps
Continuous data channels	3	3	3	3	6	6	6	6
Frequency response	20,25; 35 cps	20,25, 35 cps	20,25, 35 cps	20,25, 35 cps	40 cps	40 cps	40 cps	40 cps
Sampling rate	----	100,125 175/sec	----	100,125 175/sec	200 per sec	200 per sec	200 per sec	200 per sec
Voice channels	0	0	2 sep trans-mitters	2	2	2	2	2
Frequency response	----	----	3 kc ea.	790 cps	790 cps	790 cps	790 cps	790 cps
Sampling rate	----	----	----	3,950 per sec	----	3,950 per sec	----	3,950 per sec
Relayed PAM data channels	0	0	0	0	3	3	3	3
Synchronization words per sec	0	3	0	7	0	12	0	12
Bit rate	----	5,676 per sec	----	92,620 per sec	----	103,081 per sec	----	103,081 per sec
Bandwidth	40 kc	8.5 kc	40/6/ 6 kc	140 kc	250/ 250 kc	160 kc	250/ 250 kc	160 kc
Transmitter power	3.3 w	20 mw	3.3/5/ 2 w	0.5 w	4.5/4.5 w	2.5 w	3.5/ 3.5 w	2 w
Primary power required	60 w	10 w	109 w	30 w	110 w	50 w	90 w	40 w
System weight	8 lbs	6 lbs	20 lbs	30 lbs	18 lbs	26 lbs	15 lbs	26 lbs

TABLE II.- RF CHARACTERISTICS

Parameters	Deep Space System			Near-Earth System		
	PCM/FM	FM/FM		PCM/FM	FM/FM	
Number of transmitters	1	2		1	2	
Frequency	2,200 mc	2,150 mc	2,250 mc	220 mc	215 mc	225 mc
Bandwidth	160 kc	250 kc	250 kc	160 kc	250 kc	250 kc
Vehicle antenna gain	28 db	28 db	28 db	0 db	0 db	0 db
Ground antenna gain	51 db	51 db	51 db	30 db	30 db	30 db
System cable losses	6 db	6 db	6 db	4 db	4 db	4 db
Receiver noise figure	10 db	10 db	10 db	10 db	10 db	10 db
Receiver input S/N	10 db	10 db	10 db	10 db	10 db	10 db
Range	210,000 nautical miles	210,000 nautical miles	210,000 nautical miles	8,000 miles	8,000 miles	8,000 miles
Free space loss	210 db	210 db	210 db	162 db	162 db	162 db
Required transmitter output power	2.5 w	4.5 w	4.5 w	2 w	3.5 w	3.5 w
System input power (total)	50 w	110 w		40 w	90 w	
System weight (total)	26 lbs	18 lbs		26 lbs	15 lbs	

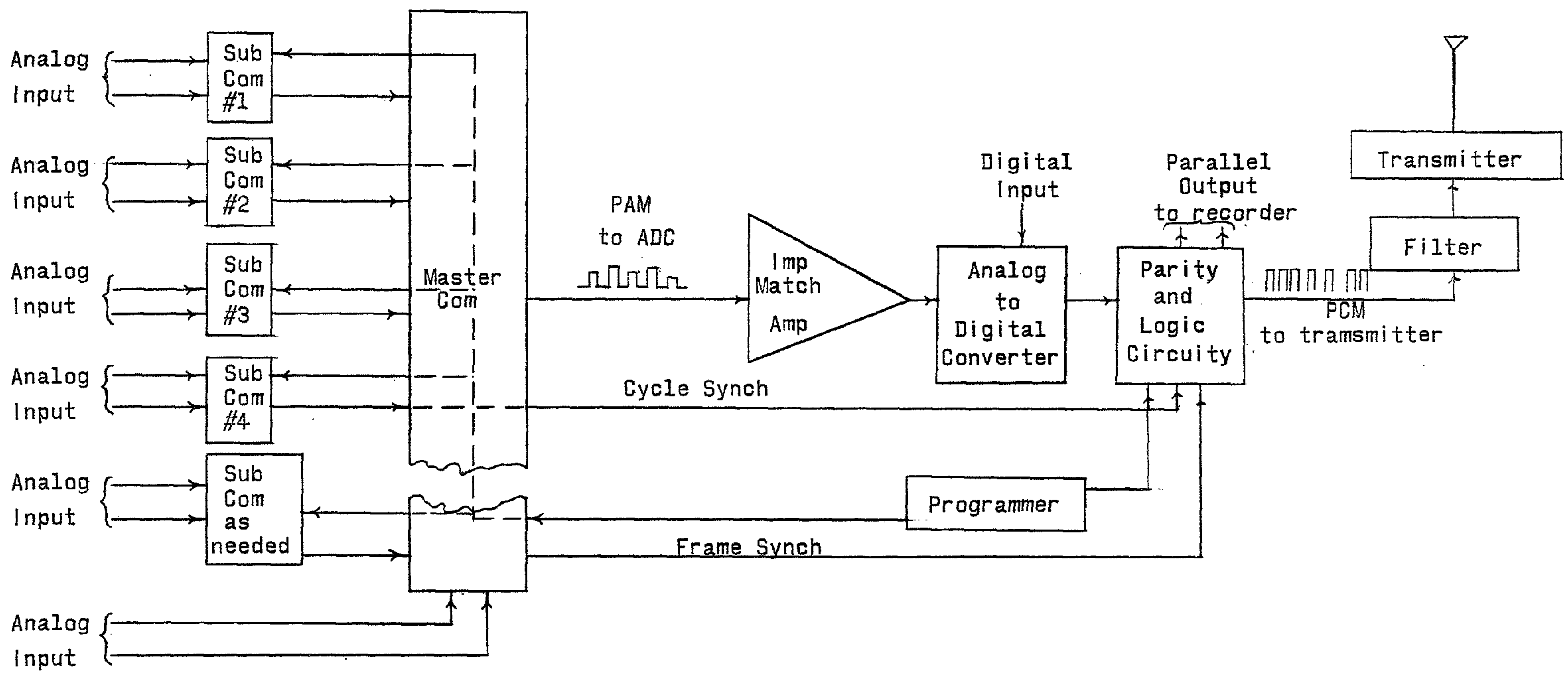
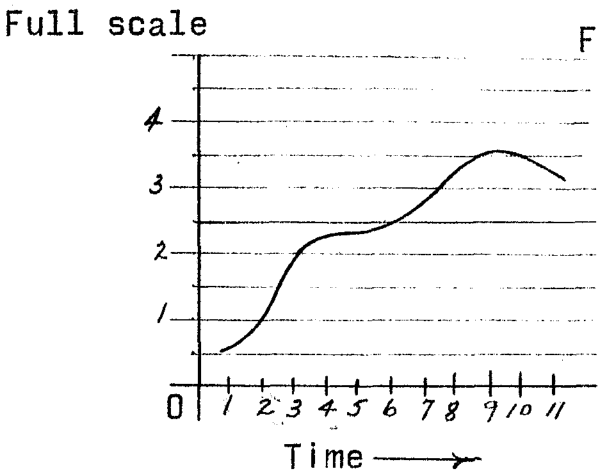
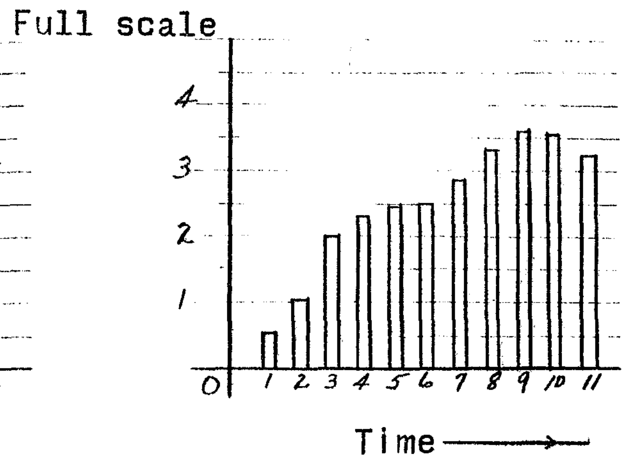


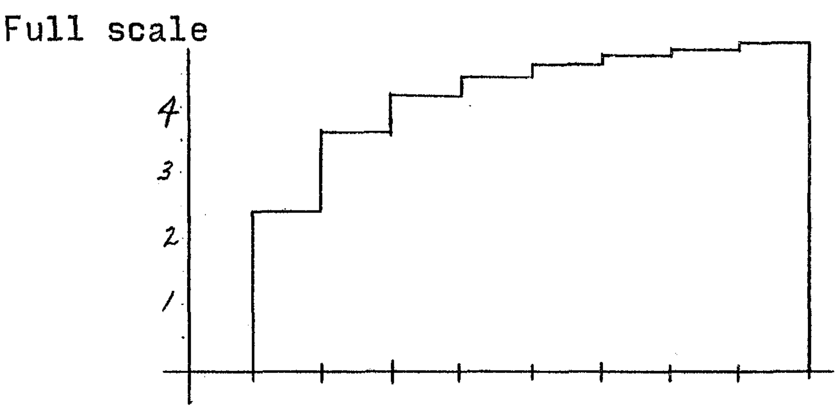
Figure 1.- A representative airborne PCM system



Analog input
(a)



Commutated analog signal
(b)



Quantizing levels for
an 8-bit system
(c)

Coded representation of
pulse 9 of (b) based on (c)
(d)

Figure 2.- Sampling, quantization, and coding